



Emission of trace gases and aerosols from biomass burning – An updated assessment

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Abstract. Since the publication of the compilation of biomass burning emission factors by Andreae and Merlet (2001), a large number of studies has greatly expanded the amount of available data on emissions from various types of biomass burning. Using essentially the same methodology as Andreae and Merlet (2001), this paper presents an updated compilation of emission
10 factors. The data from over 350 published studies were critically evaluated and integrated into a consistent format. Several new categories of biomass burning have been added, and the number of species for which emission data are presented has been increased from 93 to 121. Where field data are still insufficient, estimates based on appropriate extrapolation techniques are proposed. Based on these emission factors and published global activity estimates, I have derived estimates of pyrogenic emissions for important species emitted by the various types of biomass burning.

15 1 Introduction

Biomass burning, in the form of open vegetation fires and indoor biofuel use, is one of the largest sources of many trace gases and aerosols to the global atmosphere. For some important atmospheric pollutants, like black carbon (BC) and primary organic aerosol (POA), biomass burning is the dominant global source; based on the estimates of Bond et al. (2013), it accounts for 59% of BC emissions and 85% of POA emissions worldwide. Open vegetation fires alone represent about one-
20 third to one-half of global carbon monoxide (CO) and 20% of nitrogen oxide (NO_x) emissions (Olivier et al., 2005; Wiedinmyer et al., 2011). Fires are also a major source of greenhouse gases, including carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) (Ciais et al., 2013; Tian et al., 2016; Le Quéré et al., 2018). Numerous other studies have reached similar conclusions about the importance of biomass burning for atmospheric composition (e.g., Crutzen and Andreae, 1990; Andreae and Rosenfeld, 2008; Andreae et al., 2009; Kaiser et al., 2012; van der Werf et al., 2017).

25 The resulting perturbations of the atmospheric burdens of trace gases and aerosols have important consequences for climate, biogeochemical cycles, and human health. Aerosols from biomass burning affect the regional and global radiation balance and impact cloud properties and precipitation (Andreae et al., 2004; Andreae and Rosenfeld, 2008; Rosenfeld et al., 2008; Ward et al., 2012; Tosca et al., 2013; Rosenfeld et al., 2014; Jiang et al., 2016; Braga et al., 2017; Cecchini et al., 2017;



Hamilton et al., 2018; Thornhill et al., 2018). By shifting the proportions of direct and indirect solar radiation, they also influence primary productivity and thereby forest growth and agricultural production (Artaxo et al., 2009; Rap et al., 2015; Malavelle et al., 2019; McKendry et al., 2019). Fires mobilize nutrients, such as nitrogen, phosphorus, and potassium, which can deplete local ecosystem nutrient reservoirs on one hand and provide nutrients to other ecosystems by atmospheric transport on the other (Andreae, 1991; Andreae et al., 1998; Mahowald et al., 2008; Chen et al., 2010b). The volatile organic compounds (VOCs) and NO_x in biomass smoke undergo smog photochemistry in the atmosphere, leading to the production of ozone and other pollutants, which impact plant productivity (Crutzen and Andreae, 1990; Andreae, 1991; Pacifico et al., 2015; Yue and Unger, 2018). These gaseous pollutants, and even more so the particulate matter emitted from biomass burning, pose grave risks to human health (Naeher et al., 2007; Dennekamp et al., 2015; Knorr et al., 2017; Apte et al., 2018). Recent estimates of global excess mortality from outdoor air pollution range from 4.2 to 8.9 million annually (Cohen et al., 2017; Lelieveld and Pöschl, 2017; Shiraiwa et al., 2017; Burnett et al., 2018; Lelieveld et al., 2019), with smoke from open vegetation burning accounting for as much as 600,000 premature deaths per year globally (Johnston et al., 2012). In addition to outdoors exposure, pollution from indoor solid fuel use, much of it biofuel burning, has been estimated to cause 2.8 million premature deaths annually (Kodros et al., 2018).

In view of the immense impact of biomass burning emissions on climate, ecosystem function, and human well-being, it is disconcerting that large uncertainties persist regarding the amounts emitted and their spatial and temporal distribution. For bottom-up emissions estimates, two basic types of information are required: the amount of the various types of biomass burned as a function of time and space and the emission factors for the various emitted species, i.e., the amount of a given species emitted per unit mass of biomass burned. Considerable effort has gone into quantifying the magnitude of open biomass burning by remote sensing approaches (Mouillot et al., 2006; Reid et al., 2009; Mieville et al., 2010; Wiedinmyer et al., 2011; Kaiser et al., 2012; Ichoku and Ellison, 2014; Darmenov and da Silva, 2015; Chuvieco et al., 2016; van der Werf et al., 2017), but the estimates in these studies of the annual amounts of carbon released still range over a factor of three from 1.5 to 4.7 Pg a^{-1} . A model intercomparison based on state-of-the-art dynamic global vegetation models (DVGMs) yielded an even wider range of 1.0 to 4.9 Pg a^{-1} (Li et al., 2019).

Efforts to narrow the uncertainties in the emission factors for the large number of species emitted from the diverse types of burning are ongoing in the form of field measurements and laboratory studies. The results of these studies are, however, widely dispersed among hundreds of papers in a large number of journals, each dealing with a particular campaign or experiment. Over the last two decades, there have been two efforts to synthesize these data, one by Andreae and Merlet (2001; below referred to as A&M2001) and the other by Akagi et al. (2011). As part of the The Fire INventory from NCAR (FINN) model, Wiedinmyer et al. (2011) selected data from these two sources into a “best estimate” set of emission factors. In the present study, I am presenting an updated set of emission factors, which includes the results of studies published since the two previous compilations. It provides emission estimates for 28 more chemical species, for which measurements have become available since A&M2001, as well as an extended set of burning types. The extratropical forest category is differentiated into boreal and temperate forest burning, domestic biofuel use is separated into non-dung and dung burning, and peat fires and



domestic waste burning are added as new categories. Based on these emission data and recent activity estimates, I present a compilation of global emission amounts and make some recommendations regarding priorities for future investigations.

2 Methods

2.1 Data selection

5 This paper applies the same methodological approach as A&M2001, and therefore the methods section will only provide a brief overview of the definitions and calculation methods used and highlight those points where the present approach differs from the previous one. For all other details, the reader is referred to A&M2001. The original data, which form the basis of the emission factor averages presented in Table 1, can be found in an Excel spreadsheet in the Supplement.

10 With few exceptions, I only used results from field measurements in young fire plumes for the compilation of the emission factor data in Table 1. Ideally, these measurements had been made within minutes after the smoke was released from the fires to avoid significant chemical changes during atmospheric aging, especially in the case of reactive trace gases. This is only possible, however, when sampling at the ground or from aircraft very close to the fire. In many other cases, aircraft were sampling at some distance from the fires, often without actually knowing the exact location of the fire. In such cases, I have rejected the data for the more reactive trace gases. A special case is presented by emission data calculated from remote sensing
15 by either satellite measurements or ground-based Fourier Transformation Infrared (FTIR) spectrometry. Here, the authors have often included a correction for atmospheric transformations, using model calculations involving transport times and reaction rates of the species concerned. Because of their large spatial and temporal coverage, such measurements are quite valuable, and I have therefore included some of them in this assessment, as long as they were either dealing with long-lived species or used appropriate correction methods (Rinsland et al., 2007; Mebust et al., 2011; Tereszchuk et al., 2011; Tereszchuk et al.,
20 2013; Schreier et al., 2015; Viatte et al., 2015; Lutsch et al., 2016; Adams et al., 2019). They can be compared with in-situ measurement results by referring to the original data in the Supplement spreadsheet.

Another special case are the emission factors for gaseous elemental mercury (Hg^0). Here, only relatively few actual field measurements are available for most of the combustion types listed in Table 1. Therefore, I have followed the approach of Friedli et al. (2009) and included Hg^0 emission factors from studies that are based on the Hg content of the fuels and the
25 assumption of total volatilization of Hg from the fuel during combustion, which appears well justified for this volatile element.

Generally, the results from laboratory combustion studies have not been included in the emission factors for the different fire types in Table 1, but they are given for comparison in a separate column in the Table. The reason for this decision is that such experiments usually do not reproduce realistic burning conditions in the field. For example, it has been shown that the emissions of many trace gases are strongly dependent on fuel moisture, temperature, and other fire environment parameters
30 (e.g., Chen et al., 2010a; Robertson et al., 2014; Liu et al., 2017; Thompson et al., 2019). The fuels in lab experiments, however, are typically well aged and dried, and have a much lower moisture content than fuels in the field. This can be seen in the values of the modified combustion efficiency [MCE; the ratio of $\Delta\text{CO}_2/(\Delta\text{CO}_2+\Delta\text{CO})$] in many lab studies, which are much higher



than those typical in field burns, e.g., the study by Sirithian et al. (2018), who reported a mean MCE of 0.9996 in a lab study on biofuel burning. Therefore, lab results are only used in some special cases, where little or no field data are available and where the lab data appear representative based on their MCE, e.g., Christian et al. (2003). Some lab data are also used as estimates in Table 1 and are shown in italics.

5 The studies on emissions from biofuel burning for cooking or heating represent a borderline case, as they are often conducted in a laboratory environment, but with an effort to simulate actual fuel use conditions and stove setups used in the households. Here, I have favored studies performed in actual households, but also included results from lab studies that appeared to realistically emulate field conditions. Results from modern residential biofuel combustion units, such as automated pellet burners, etc., have not been included.

10 2.2 Definitions

In the literature, emission information is generally found as either emission ratios (ER) or emission factors (EF). Strictly speaking, most data presented as “emission ratios” are actually enhancement ratios (EnR), often also referred to as normalized excess mixing ratios (NEMR; Akagi et al., 2011). They are defined as the ratio of the excess concentration of the species of interest in the plume, (ΔX), to the excess concentration of a reference species, e.g., carbon monoxide (ΔCO),

$$15 \quad EnR_{X/CO} = \frac{\Delta X}{\Delta CO} = \frac{(X)_{plume} - (X)_{backgr}}{(CO)_{plume} - (CO)_{backgr}}$$

where Δ stands for the difference between the concentrations in the plume and in the background atmosphere. Because of its abundance in fire emissions and its relatively low ambient background concentration, CO is most commonly used as reference species, but other gases, such as carbon dioxide (CO_2), methane (CH_4), or acetonitrile have also been used. The use of CO_2 can introduce large errors because it also has strong surface sources and sinks, which can lead to erroneous estimates of the background concentration, as discussed in detail in Yokelson et al. (2013a). An enhancement ratio can be interpreted as an emission ratio when it is assured that the concentrations of both species X and the reference species have not been affected by chemical production or loss since the emission, and that both concentrations have changed proportionally during dilution of the plume with background air. In the case of very long-lived substances, e.g., acetonitrile, EnRs can be very close to ERs even after days, while for reactive compounds, e.g., nitric oxide (NO), significant changes can occur in minutes. For further discussion of the advantages and disadvantages of the different reference gases, the effects of flaming vs. smoldering combustion, and ground-based vs. airborne sampling, see A&M2001 and Akagi et al. (2011).

While the measurement of ERs is relatively easy in the field, because it requires only the measurement of the atmospheric concentrations of target and reference species, it is generally desirable to obtain the amount of a species emitted per unit mass of fuel burnt, i.e., the emission factor, EF. For biomass burning, this is usually expressed as the mass of target species X released per mass of dry fuel burnt, in units of $g\ kg^{-1}$. This, however, requires knowledge of the mass of fuel burned, which is readily measured in the lab, but difficult to obtain in the field. As an alternative, the mass balance method can be used, where the mass of fuel burned is approximated by the sum of carbon contained in the emitted carbon species (CO_2 , CO, CH_4 , volatile



organic compounds [VOC], organic aerosol carbon [OC]), divided by the carbon fraction in the fuel. Often, the carbon mass is approximated by the sum of CO₂ and CO, and a default fuel carbon content of 45% is assumed.

2.3 Conversion of units

To provide a uniform representation of the various types of data found in the literature in the form most useful to modelers, all emission data was converted to emission factors, in units of g kg⁻¹ dry fuel. Where emission factors relative to other fuel mass indicators was given, e.g., the mass of carbon burned or released, I applied appropriate conversion factors, such as the known or assumed carbon content of the fuel. Very frequently in the literature, only EnRs or ERs in units of mol/mol are provided. These can in principle be easily converted to EFs by the following equation:

$$EF_{(X/Y)} = ER_{(X/Y)} \frac{MW_X}{MW_Y} EF_Y$$

where ER_(X/Y) is the emission ratio of species X relative to the reference species Y, MW_X and MW_Y are the molecular weights of the species X and the reference species Y, and EF_Y is the emission factor of the reference species. Since the value of EF_Y is usually not known, the mean EF_Y for the appropriate type of fire (forest, savanna, etc.) was applied.

2.4 Estimates where no data are available

For some combinations of fire type and emitted species, no suitable field data is available to provide a basis for estimating EFs. Where possible, I have used appropriate methods to derive estimates based on other information, shown in italic font in Table 1. For each species, the estimation method is given in column EM. For species predominantly emitted during smoldering combustion, e.g., most VOCs, I have based the estimate on the assumption that their emission factors for the various fire categories are proportional to those of CO for the same categories. The estimate was then obtained by calculating the mean of the ratios ER_X/ER_{CO} for the fire categories with available data and multiplying this mean by the ER_{CO} of the fire category for which an estimate was needed (labeled CO in column EM). Where no suitable ratios ER_X/ER_{CO} were available from field studies, the lab ratio was used instead (labeled LV). For species emitted predominantly in flaming combustion, the mean of the ERs from fire categories with available data, weighted by the amounts of biomass globally burned in those categories, was used (labeled AV). Subjective “best estimates” are labeled BE.

3 Results and discussion

3.1 Combustion process and pyrogenic emissions

Our fundamental understanding of the biomass combustion process remains unchanged since the 1990s, as reviewed in A&M2001 and other papers (Lobert and Warnatz, 1993; Yokelson et al., 1996; Yokelson et al., 1997; Akagi et al., 2011), and will thus be summarized here only briefly. As the combustion front of a fire moves towards the uncombusted fuel, the fuel is heated by radiative and sensible heat transfer, leading first to evaporation of water and other volatiles, then to pyrolytic



decomposition and the release of volatile and semivolatile (tar) decomposition products. When this released mixture ignites, flame chemistry sets in, which breaks down the more complex pyrolysis compounds to small molecules and radicals, but also produces new larger molecules by radical chemistry, such as alkynes, polycyclic aromatic hydrocarbons (PAH), soot, and organohalides. Once most volatile matter is consumed during flaming combustion, the remaining char undergoes gas-solid reactions between oxygen and carbon at the fuel surface, called the smoldering phase, in which a large fraction of the fuel carbon is released as CO. In a typical vegetation fire, all these processes occur simultaneously as the fire propagates through the fuel, so that the fire plume at any place and time contains mixtures of pyrolysis, flaming, and smoldering combustion products in variable proportions.

Depending of the vegetation type and burning conditions, the relative amounts of fuel consumed by flaming and smoldering combustion can vary considerably. Dry grassland fires, for example, are dominated by flaming combustion and a rapid passage of the fire front, with little residual smoldering. Forest fires, on the other hand, especially those in fuels with relatively high fuel moisture and large diameters, have a long phase of residual smoldering combustion (RSC), during which larger-diameter fuels are consumed over time spans of up to several days (Ward and Hardy, 1991; Ward et al., 1992; Yokelson et al., 1997; Bertschi et al., 2003; Hao and Babbitt, 2007; Burling et al., 2011; Akagi et al., 2013; Geron and Hays, 2013; Urbanski, 2014; Reisen et al., 2018). The smoldering mode of combustion can become dominant in peatland fires, which often proceed without a flaming phase and below ground (Bertschi et al., 2003).

Because the rate of heat release during RSC is relatively low and much of it occurs during nighttime, the resulting emissions tend to accumulate close to ground and confined in a nocturnal boundary layer. This presents serious problems for measuring accurate emission factors for RSC emissions. Aircraft studies will completely miss these emissions, as they are not lofted in the form of discrete plumes to aircraft altitudes, but only mixed upward during daytime convection where they get lost in the ambient atmosphere (Guyon et al., 2005). Ground-based studies during the RSC phase can obtain ERs of trace species to CO, but these are difficult to relate to the corresponding amount of fuel burned, because this would require knowledge of the ER(CO/CO₂). This turns out to be practically impossible to measure, since the CO₂ concentration near ground, especially at night, is more strongly influenced by respiration and photosynthesis than by RSC emissions, thus invalidating attribution of any CO/CO₂ correlations to RSC emissions. For example, in our studies in the Amazon Basin we sometimes had nighttime concentrations of several ppm CO, but with no significant correlation to CO₂ (Guyon et al., 2005).

Because the flaming phase is characterized by CO₂ being the dominant combustion product by far, while the smoldering phase yields relatively large amounts of CO, the MCE has been established over the last two decades as the key metric representing the relative role of flaming vs. smoldering combustion in vegetation fires, spanning a range of 0.77 in peat fires to 0.98 in some grassland fires (see Supplement). Mean MCE values for the different combustion categories are presented in Table 1.

Since the MCE was introduced by Ward and Radke (1993), numerous papers have used this metric and have shown significant negative correlations for many trace gases between emission factors and MCE, especially for the various VOCs that are emitted predominantly during smoldering combustion (e.g., Korontzi et al., 2003; Yokelson et al., 2003; Yokelson et



al., 2008; Soares Neto et al., 2009; Urbanski et al., 2009; Burling et al., 2011; Urbanski, 2013; Yokelson et al., 2013b; Liu et al., 2014; Urbanski, 2014; Collier et al., 2016; Coffey et al., 2017; Fortner et al., 2018; Hodgson et al., 2018; Reisen et al., 2018). Unfortunately, the correlation slopes between EFs and MCE vary considerably between studies in different fuels and burning environments, so that a general parameterization of EFs based on observed or modeled MCE remains problematic. As an illustration, I show in Fig. 1a and 1b plots of the EFs of ethene (C_2H_4) and ethane (C_2H_6) vs MCE, based on the studies in the supplemental spreadsheet. In both cases, the results scatter widely, and especially the data from the lab studies, biofuel burning, peat fires, and RSC-dominated fires introduce a large amount of scatter. The poor correlation between EFs and MCE has been noted previously (Yokelson et al., 1997; Bertschi et al., 2003; Burling et al., 2011; Urbanski, 2014). In the case of ethene, the correlation using all data points is not significant ($R^2 = 0.07$). However, when only the data from open vegetation fires are included (and after removing three outliers), the correlation improves to an R^2 of 0.27. For ethane, the correlation coefficient is $R^2 = 0.38$ for all data, but does not improve substantially by removing the peat fire data. These results suggest the potential of using MCE as a meaningful, but rough predictor of EFs for at least some species. This approach is not pursued further here, but the data in the supplement can be used by investigators to derive such relationships for specific compounds and combustion types of interest.

Using MCE as a predictor variable may be an alternative to providing separate EFs for smoldering and flaming combustion, which has been frequently requested by the modeling community, but for which there is still not enough data to provide robust estimates, as we had already remarked previously in A&M2001. However, if vegetation fire models are able to provide estimates of the contribution of flaming and smoldering combustion from a given fire, the resulting MCE could be predicted. This could then form the basis of a more fire-specific prediction of trace gas and aerosol emissions based on MCE correlations. An alternative approach was proposed by Korontzi et al. (2003), who showed a correlation between vegetation greenness and MCE, which allowed the prediction of seasonally-dependent emissions from African savanna fires (Korontzi, 2005).

3.2 Emission factors for chemical species from the various combustion categories

In Table 1, I present the updated estimates of emission factors for the combustion categories, savanna/grassland, tropical forest, temperate forest, boreal forest, peat fires, open agricultural waste burning (in the fields), biofuels (excluding dung), dung cakes, charcoal making, charcoal burning, and garbage burning. For information purposes, I also include a column for the results of laboratory studies. The averages in this column can only be seen as general indications, since all types of fuels and burning methods are included, but the original data and references are provided in the supplement for readers interested in the details. As more data have become available, it is now possible to split the extratropical forest category into temperate and boreal forest. The transition between these two types is not always clear, but in general, I have followed the authors' choice of category; where this was not possible I have taken a latitude of 60 °N as boundary.

The large number of studies on residential biomass burning that have been published in the last two decades has made it possible to separate dung cakes from the other biofuels, such as fuel wood and agricultural residues. As mentioned above, I



only included studies that used fireplaces and traditional or simple “improved” stoves, as they are used in developing countries, and not modern appliances, such as automated pellet stoves. The publication of a few papers that provided emissions data for open garbage burning, still quite prevalent in many countries and a serious source of pollution especially in urban areas, has made it possible to provide EFs for this category. Obviously, the categories used here are still quite highly aggregated, but they correspond closely to the fire types used in many global modeling studies, such as those involved in the Fire Modeling Inter-comparison Project (FireMIP) (Li et al., 2019) and in model or satellite based emission inventories (Wiedinmyer et al., 2011; Kaiser et al., 2012; Ichoku and Ellison, 2014; Darmenov and da Silva, 2015; van der Werf et al., 2017). Should a reader require less highly aggregated data, they can use the supplement to split the data into subcategories or even use the supplemental references to get back to the original literature.

As in A&M2001 and in Akagi et al. (2011), the amount of information for any given combination of species and fire category varies greatly - for some combinations we have no measurements at all and for others there are as many as 50 values. Accordingly, the uncertainty of the estimates is also highly variable. In Table 1, I am using the same convention as in A&M2001 to represent the uncertainty: When three or more values (based on independent references) are available for a given table cell, the results are given as means and standard deviations ($x \pm s$). In the case of two available measurements, they are given as a range, and where only a single measurement is available, it is given without an uncertainty estimate. For single measurements, it can usually be assumed that the uncertainty is no less than a factor of three.

In spite of the fact that this paper is based on data from over 350 publications, rather than the 130 papers that formed the basis for A&M2001, Table 1 shows that there are still many species for which there are little or no field data available. For example, there are still no field measurements of the emission factors for the alkyl amines, which have recently become implicated in aerosol nucleation and new particle formation (Smith et al., 2010; Almeida et al., 2013; Kürten et al., 2014). In view of the importance of the number concentrations of aerosol particles, especially cloud condensation nuclei, for climate change, it is unfortunate that there have only been a few additional measurements of their emission factors in the last two decades. Another climate-relevant component, for which we have no emission data at this time, is brown carbon (Andreae and Gelencsér, 2006), which has been shown to account for about half of the aerosol light absorption by biomass smoke at 401 nm (Selimovic et al., 2019) and 25-45 % at 550 nm (Tian et al., 2019).

The most problematic uncertainty, however, pertains to the emission factors of CO₂ and CO from forest fires, which is surprising in view of the many available estimates. This uncertainty stems from the inadequate knowledge of the contribution from RSC, which has already been referred to above, and which may be responsible for large mismatches between bottom-up predictions of CO emissions and remote-sensing measurements from satellite (Pechony et al., 2013; Deeter et al., 2016). The uncertainty regarding the $\Delta\text{CO}/\Delta\text{CO}_2$ emission ratio also seriously hampers our ability to separate the influence of the emissions from deforestation burning from those of biological carbon fluxes in regional carbon budgets (Andreae et al., 2012). For example, the uncertainty of the $\Delta\text{CO}/\Delta\text{CO}_2$ ratios of tropical forest burning is large enough that it can even change the sign of the net carbon flux between the Amazon forest and the atmosphere (Gatti et al., 2014).



3.3 Emissions from global biomass burning

In 2001, we estimated the total amount of biomass burned by all combustion types to be 8.6 Pg dry matter annually with an uncertainty of $\pm 50\%$ (A&M2001). This estimate was based on bottom-up inventories and had not yet benefitted from remote-sensing detection and quantification of fires. At present, there are several operational fire detection and emission estimation products based on remote sensing. Three of them use a bottom up approach based on burnt area and hotspot detection: Fire INventory from NCAR (FINN; Wiedinmyer et al., 2011), Fire Locating and Modeling of Burning Emissions (FLAMBE; Reid et al., 2009), and Global Fire Emissions Database (GFED; van der Werf et al., 2017). The other three products are top-down, based on fire radiative power (FRP): Quick Fire Emission Dataset (QFED; Darmenov and da Silva, 2015), Global Fire Assimilation System (GFAS; Kaiser et al., 2012), and Fire Energetics and Emissions Research (FEER; Ichoku and Ellison, 2014). The amounts of biomass burned annually in open fires estimated by these systems still spans a wide range, from 4.3 Pg (GFAS) to 11.6 Pg (FLAMBE) (for the FRP-based products, which do not use biomass burnt in their calculations, the biomass estimate was based on the stated emission of carbon compounds and an assumed carbon fraction of 45 % in the biomass).

For domestic biofuel use, there are three recent global estimates: 2.1 Pg a⁻¹ (Fernandes et al., 2007), 2.5 Pg a⁻¹ [S. J. Smith, personal communication, 2019, based on the Community Emissions Data System (CEDS) model (Hoesly et al., 2018)] and 2.3 Pg a⁻¹ [Z. Klimont, personal communication, 2019, based on the methodology in Klimont et al. (2017)]. These recent estimates are all somewhat lower than those of A&M2001 (2.9 Tg a⁻¹) and Yevich and Logan (2003) (3.1 Tg a⁻¹). For charcoal burning, I am also using the estimate of 53 Tg a⁻¹ given for 2014 by FAO (2015), and for charcoal making I am assuming a 25% yield of charcoal relative to dry wood (Yevich and Logan, 2003).

Combining these estimates of open and domestic burning yields a mean estimate of 8.8 Pg (with a range of 6.4 to 14.1 Pg) dry biomass burned annually. Interestingly, this is almost identical to the values given in A&M2001: 8.6 Pg a⁻¹, with an estimated range of 4.3 to 12.9 Pg a⁻¹). Table 2 summarizes these emission estimates. For the various categories of open burning, the satellite-derived emission estimates vary greatly, in some cases by an order of magnitude. Differences in the definitions of the burning categories between the different retrieval algorithms, differing ability to detect small fires, and the fundamental difference between the burnt-area and FRP-based techniques may all play a role here.

In Table 3, I use the average of the available estimates from the different inventories shown in Table 2 as activity estimates for the combustion categories to derive emission values for major species emitted from biomass burning. For comparison, the last column in Table 3 shows the global total emissions estimated in A&M2001. The totals of the major emitted carbon species and many minor species remain fairly close to those in the previous assessment. Given the large number of measurements for the emission factors for the major species, CO₂, CO, and CH₄, the standard error of the mean is much smaller than the standard deviation, and thus the relative uncertainties of the mean for these emission factors are quite small, 1-3% for CO₂, 4-9% for CO, and 6-18% for CH₄ from the major burning categories savanna, forests, and biofuel. Consequently, the emission uncertainties for these species are completely dominated by the large uncertainties in the activity estimates.



The best independent “reality check” for these emissions may still come from the inverse modeling of the CO budget. This species is the most appropriate for such a comparison, because its emission factors are well constrained, biomass burning is a large fraction of all global sources, and there is a large body of measurements both from ground stations and remote sensing. Estimates of CO emissions from the various inversion models range from 190 to 560 Tg a⁻¹ from biofuel burning and 5 360 to 610 Tg a⁻¹ from open burning for the years around 2000 (Park et al., 2015, and references therein). The model of Park et al. (2015), which uses a joint inversion of CO concentrations and oxygen isotopic composition and therefore is likely to be the most reliable in separating the different source types, predicts CO emissions of 380 to 610 Tg a⁻¹ from open burning, 400 to 520 Tg a⁻¹ from biofuel use, and 780 to 1130 Tg a⁻¹ for all biomass burning. Using the EFs from Table 1 and the activity estimates from Table 2, we obtain a range of 390 to 1210 Tg a⁻¹ for the CO emissions from open burning, in reasonable 10 agreement with the inverse results. The range of biofuel CO emissions estimated from Tables 1 and 2 is only 181-196 Tg a⁻¹, accounting for less than one-half of the inverse estimate. This suggests either that the amount of biofuel use is significantly underestimated in present bottom-up budgets, or that the inversions attribute some of the open burning inaccurately to biofuel use. This could likely be the case for agricultural burning, which uses similar fuels and takes place in similar regions as biofuel use.

15 Major differences between the present emission estimates and A&M2001 are seen for the oxygenated volatile organic compounds and for HCN, which all are significantly greater in the present assessment than in A&M2001. This is due to the large number of new and more accurate emission factor measurements for these compounds, which have been made possible by improvements in analytical techniques since the 1990s.

4 Conclusions

20 We are left with the somewhat frustrating conclusion that, in spite of the great progress in emission factor measurements and detection and quantification of fires, the overall uncertainty of biomass burning emissions has not decreased significantly for most substances since our analysis of almost twenty years ago. Evidently, there is a great need for improved accuracy in the activity estimates, for open burning and especially for biofuel use. For open burning, coordinated regional CO studies in regions and at times of high biomass burning activity, including both top-down and bottom up remote sensing 25 approaches as well as inversions, may be a way to resolve discrepancies and improve accuracy. This would be of great benefit for testing and improving fire emission models, which also give quite divergent results and have difficulties in capturing interannual variations and temporal trends (Li et al., 2019). The modelled estimates of carbon emitted from open burning in the nine models participating in the FireMIP project spans from 1.0 to 4.9 Pg a⁻¹ (Li et al., 2019).

30 With regard to emission factors, Table 1 can serve as a guide to prioritizing future research activities. Photochemically active species and toxic compounds for which there are only a few measurements from important fire types deserve more intense study. An example is the emission of PAHs, where we have only one study from boreal fires and none at all from tropical forest fires. Given the toxicity of these compounds and the increasing exposure of populations in these regions to



biomass smoke as a result of climate change and population growth, this seems an important knowledge gap. I have already referred to the lack of field measurements of alkyl amine emissions, which may be of importance for new particle formation. In view of the grave health risk associated with aerosol particles (see, e.g., Lelieveld et al., 2019, and references therein) and the growing exposure to wildfire smoke in areas like the western U.S.A., the accuracy and fire condition dependence of PM emissions need to be improved. Emphasis should be on field measurements under a variety of representative conditions, to represent the influence of parameters like fuel moisture and fire weather.

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Table 1: Emission factors for pyrogenic species emitted from various types of biomass burn^a

Species	Savanna and grassland		Tropical forest		Temperate forest		Boreal forest		Peat Fires		Agricultural residues (open)					
	average	std.dev.	N	average	std.dev.	N	average	std.dev.	N	average	std.dev.	N				
MCE	0.94	0.02	48	0.91	0.03	15	0.90	0.89	0.04	21	0.79	0.02	5	0.92	0.06	30
CO ₂	1660	90	31	1620	70	9	1570	1530	140	14	1550	130	5	1420	240	25
CO	69	21	49	105	40	15	113	121	47	22	250	23	5	74	50	34
CH ₄	2.5	1.0	47	6.2	2.0	13	5.2	5.5	2.5	20	9.3	1.5	5	5.5	5.7	17
Total non-methane hydrocarbons	3.5	1.2	13	5.6	1.5	4	13.4	6.0	2.9	8	7.9	-	0	5.8	5.1	11
C ₂ H ₂	0.32	0.29	28	0.35	0.39	6	0.31	0.28	0.13	12	0.11	0.05	3	0.29	0.24	10
C ₂ H ₄	0.85	0.38	25	1.11	0.24	5	1.12	1.54	0.66	7	1.47	0.72	3	0.96	0.52	12
C ₂ H ₆	0.41	0.32	28	0.88	0.23	7	0.69	0.97	0.37	14	1.85	1.5-2.2	2	0.65	0.46	10
C ₃ H ₄	0.071	0.111	8	0.103	-	1	0.05	0.062	0.031	3	0.006	-	1	0.17	0.01-0.34	2
C ₃ H ₆	0.46	0.45	26	0.86	0.41	5	0.67	0.40	0.45	7	1.14	1.07-1.21	2	0.41	0.26	15
C ₃ H ₈	0.13	0.18	20	0.53	0.15-0.91	2	0.27	0.19	0.10	8	0.99	-	1	0.17	0.07	9
1-Butene	0.082	0.049	13	0.073	0.020-0.125	2	0.12	0.061	0.143	4	0.46	0.18-0.74	2	0.083	0.043	8
i-Butene	0.041	0.019	6	0.109	-	1	0.086	0.074	0.032	3	0.31	-	1	0.079	0.040	3
trans-2-Butene	0.020	0.012	11	0.033	0.016-0.050	2	0.037	0.031	0.018	3	0.078	-	1	0.036	0.014	6
cis-2-Butene	0.017	0.010	11	0.031	0.020-0.042	2	0.038	0.039	0.016	3	0.062	-	1	0.027	0.010	6
Butadiene	0.095	0.057	13	0.15	-	0	0.125	0.068	0.030	4	0.22	0.19-0.26	2	0.16	0.24	10
n-Butane	0.021	0.011	14	0.041	-	1	0.081	0.060	0.051	6	0.32	-	1	0.043	0.029	7
i-Butane	0.007	0.005	13	0.015	-	1	0.031	0.026	0.051	6	0.090	-	1	0.016	0.017	7
1-Pentene	0.022	0.009	6	0.058	-	1	0.048	0.024	0.025	3	0.110	-	1	0.015	0.011	5
2-Pentenes	0.014	0.020	4	0.026	-	0	0.043	0.023	0.006-0.016	2	0.062	-	1	0.023	0.005	4
n-Pentane	0.007	0.008	11	0.014	-	1	0.034	0.026	0.015	6	0.24	-	1	0.042	0.057	7
2-Methyl-butenes	0.025	0.037	7	0.075	-	1	0.056	0.045	0.015	6	0.125	-	1	0.026	0.013	5
2-Methyl-butane	0.008	0.009	10	0.008	-	1	0.017	0.011	0.016	6	0.123	-	1	0.019	0.014	5
n-Pentadienes	0.048	-	1	0.042	-	0	0.035	0.016	0.049	4	0.049	-	0	0.030	-	0
Isoprene	0.101	0.158	10	0.22	0.016-0.42	2	0.10	0.05	0.074	1	0.52	0.05-0.98	2	0.17	0.26	7
Cyclopentadiene	0.019	0.016	4	0.022	-	0	0.041	0.019	0.03	0	0.025	-	0	0.007	0.002	3
Cyclohexadiene	0.026	-	1	0.036	-	0	0.027	0.025-0.029	0.041	2	0.041	-	0	0.001	-	1
4-Methyl-1-pentene	0.049	-	1	0.049	-	1	0.041	-	0.044	0	0.09	-	0	0.005	0.007	4
2-Methyl-1-pentene	0.018	0.032	4	0.037	-	3	0.058	0.027	0.043	3	0.11	-	1	0.026	-	0
1-Hexene	0.043	0.018	6	0.065	-	1	0.084	0.022	0.109	0	0.14	-	0	0.012	0.005	3
Hexadienes	0.006	-	1	0.007	-	0	0.006	0.006-0.006	0.008	2	0.017	-	0	0.005	-	0
n-Hexane	0.018	0.028	10	0.032	-	0	0.032	0.040	0.054	3	0.14	-	1	0.032	0.059	4
Isobutenes	0.019	0.028	3	0.048	-	0	0.026	0.038	0.013	8	0.054	-	1	0.067	0.115	4
Heptanes	0.016	0.019	6	0.024	-	0	0.029	0.026	0.021	2	0.112	-	1	0.031	0.033	4
Octenes	0.021	0.027	3	0.012	-	1	0.036	0.023	0.021	5	0.065	-	1	0.003	-	1
Terpenes	0.104	0.096	5	0.15	-	0	0.117	1.95	1.53	9	0.08	0.005-0.16	2	0.029	0.031	3
Benzene	0.33	0.22	18	0.38	0.05	4	0.39	0.20	0.57	16	0.87	0.78-0.95	2	0.28	0.20	15
Toluene	0.20	0.14	16	0.23	0.04	4	0.25	0.17	0.35	15	0.45	0.37-0.52	2	0.16	0.10	15
Xylenes	0.086	0.077	8	0.086	0.049	3	0.16	0.090	0.11	9	0.23	-	1	0.09	0.11	9
Ethylbenzene	0.022	0.010	8	0.043	0.034	3	0.041	0.018	0.038	10	0.042	-	1	0.045	0.049	7
Styrene	0.056	0.029	6	0.028	-	0	0.066	0.028	0.13	8	0.055	0.027-0.082	2	0.043	0.029	6
PAHs	0.012	0.016	4	0.14	-	0	0.017	0.019	0.6	7	0.39	-	1	0.033	0.017	4
Methanol	1.35	0.47	14	2.8	0.5	4	2.2	0.9	2.33	19	2.5	0.4	3	2.6	1.4	8
Ethanol	0.036	0.017-0.055	2	0.067	-	0	0.076	0.089	0.058	7	0.16	-	0	0.05	-	0
1-Propanol	0.025	-	1	0.038	-	0	0.041	-	0.044	0	0.090	-	0	0.027	-	0
2-Propanol	0.08	-	0	0.12	-	0	0.13	-	0.14	0	0.29	-	0	0.09	-	0
Butanols	0.11	0.008-0.21	2	0.009	-	1	0.064	0.029-0.098	0.072	2	0.15	-	0	0.011	-	1
Cyclopentanol	0.033	-	1	0.032	-	1	0.038	-	0.040	0	0.083	-	0	0.016	-	1
Phenol	0.43	0.19	7	0.23	0.006-0.45	2	0.25	0.09	0.63	3	0.47	0.42-0.51	2	0.50	0.49	4
Formaldehyde	1.23	0.65	16	2.40	0.63	3	2.08	0.70	1.75	15	1.07	0.44	3	1.8	1.2	7
Acetaldehyde	0.84	0.65	9	2.26	1.55-2.97	2	1.07	0.62	0.81	13	1.16	0.70-1.63	2	1.7	1.2	4
Hydroxyacetaldehyde (glycolaldehyd.)	0.21	0.18	5	0.42	-	0	0.39	1	0.48	1	0.11	-	1	3.2	2.3-4.1	2
Glyoxal	0.40	-	0	0.60	-	0	0.65	-	0.69	0	0.74	-	0	0.23	-	1
Methylglyoxal	0.40	0.15-0.64	2	0.52	-	0	0.27	-	0.61	1	0.23	-	1	0.55	-	1
Acrolein (Propenal)	0.48	0.25	6	0.65	-	1	0.34	0.13	0.33	7	0.27	-	1	0.65	0.45	4
Propanal	0.053	0.009-0.097	2	0.10	-	1	0.087	0.040	0.24	4	0.33	-	0	0.18	-	1
Butanal	0.11	0.054-0.220	2	0.13	0.073-0.18	2	0.11	0.07	0.16	5	0.02	-	1	0.17	0.02-0.32	2
Methacrolein	0.11	-	0	0.15	-	1	0.14	0.18	0.12	3	0.38	-	0	0.28	-	1
Crotonaldehyde	0.25	-	0	0.24	-	1	0.40	-	0.43	0	0.88	-	0	0.42	-	1



Hexanals	0.048	0.068	3	2	0.021	0.010-0.031	0.038	0.033	4	0.038	-	0	0.08	-	0	0.020	0.011-0.03	2
Heptanals	0.003	0.001-0.005	2	1	0.005	-	0.005	-	0	0.005	-	0	0.010	-	0	0.001	-	1
Acetone	0.47	0.18	7	1	0.63	-	0.42	0.42	11	1.59	1.61	7	0.91	0.69-1.12	2	0.61	0.47	4
2-Butanone	0.13	0.1	6	1	0.50	-	0.21	0.21	5	0.16	0.04	5	0.34	0.14-0.54	2	0.60	0.29-0.90	2
2,3-Butanedione	0.35	0.2	4	1	0.73	-	0.86	0.86	5	0.34	-	1	0.32	-	1	1.23	1.15-1.31	2
1-Butene-3-one (Methylvinyl ketone)	0.23	-	1	1	0.39	-	0.109	0.109	5	0.099	0.097-0.10	2	0.057	-	1	0.48	0.25-0.70	2
Pentanones	0.015	0.006	3	0	0.059	0.028-0.090	0.033	0.033	5	0.075	-	0	0.075	-	1	0.10	0.007-0.20	2
Hexanones	0.048	-	1	0	0.057	-	0.045	0.043-0.046	2	0.066	-	0	0.14	-	0	0.040	-	0
Heptanones	0.006	-	1	1	0.002	-	0.005	-	0	0.005	-	0	0.011	-	0	0.002	-	1
Octanones	0.015	-	1	1	0.019	-	0.023	-	0	0.024	-	0	0.050	-	0	0.015	-	0
Benzaldehyde	0.102	0.097	4	0	0.027	-	0.132	0.077	3	0.096	-	0	0.056	-	1	0.039	0.008-0.07	2
Acetol (hydroxyacetone)	0.56	0.3	3	0	1.13	-	1.6	-	1	1.6	-	0	0.64	0.42-0.86	2	1.74	0.29	3
Furan	0.29	0.14	8	0	0.33	0.25-0.41	0.41	0.26	8	0.36	0.28-0.44	2	1.07	0.74-1.4	2	0.50	0.47	3
2-Methyl-furan	0.20	0.14	6	3	0.28	0.28	0.34	0.21	5	0.43	-	0	0.31	0.12-0.50	2	0.53	0.519	3
3-Methyl-furan	0.010	0.004	3	0	0.055	0.030-0.080	0.034	0.016	3	0.052	-	0	0.11	-	0	0.076	0.003-0.15	2
2-Ethylfuran	0.005	0.001-0.009	2	1	0.003	-	0.016	0.012	5	0.008	-	0	0.026	-	0	0.0005	-	1
2,4-Dimethyl-furan	0.063	-	1	0	0.024	-	0.012	-	0	0.013	-	0	0.14	-	1	0.098	-	1
2,5-Dimethyl-furan	0.009	0.067	4	0	0.086	-	0.070	0.070	5	0.10	-	0	0.023	-	0	0.006	-	1
Tetrahydrofuran	0.014	0.002-0.016	2	1	0.017	-	0.001	0.0005-0.0017	2	0.011	-	0	0.026	-	0	0.005	-	1
2,3-Dihydrofuran	0.045	0.013-0.015	2	1	0.003	-	0.003	0.001-0.004	2	0.013	-	0	0.032	-	0	0.024	0.004-0.044	2
Benzofuran	0.073	0.040	4	0	0.016	-	0.094	0.071	3	0.061	-	0	0.032	-	1	0.005	-	2
Furfural (2-Furaldehyde)	0.73	0.74	3	0	0.78	-	0.52	0.81	7	0.61	-	1	1.10	0.12-2.1	2	1.03	-	1
Methyl formate	0.159	-	1	0	0.051	-	0.024	0.022-0.027	2	0.024	-	1	0.12	-	0	0.04	-	0
Methyl acetate	0.17	0.059-0.26	2	0	0.13	-	0.095	0.058	5	0.087	-	1	0.32	-	0	0.09	-	0
Acetonitrile	0.037	0.009	3	0	0.04	0.14	0.23	0.18	13	0.31	0.10	6	0.60	-	1	0.23	0.26	6
Propionitrile	0.027	0.012-0.042	2	1	0.031	-	0.031	0.014	6	0.068	-	0	-	-	0	0.094	0.061	3
Pyrrrole	0.013	-	1	1	0.12	-	0.011	0.011-0.012	2	0.11	-	0	-	-	0	0.17	-	1
Trimethylpyrazole	-	-	0	0	0.062	-	0.085	0.085	3	0.15	-	0	-	-	0	0.22	-	1
Methylamine	-	-	0	0	-	-	-	-	0	-	-	0	-	-	0	-	-	0
Dimethylamine	-	-	0	0	-	-	-	-	0	-	-	0	-	-	0	-	-	0
Ethylamine	-	-	0	0	-	-	-	-	0	-	-	0	-	-	0	-	-	0
Trimethylamine	-	-	0	0	-	-	-	-	0	-	-	0	-	-	0	-	-	0
n-Pentylamine	-	-	0	0	-	-	-	-	0	-	-	0	-	-	0	-	-	0
2-Methyl-1-butylamine	-	-	0	0	-	-	-	-	0	-	-	0	-	-	0	-	-	0
Formic acid	0.30	0.21	14	0	0.88	0.63	1.11	1.27	12	1.91	2.24	8	0.29	0.14	3	0.86	0.89	7
Acetic acid	2.31	1.8	13	3	3.3	0.8	2.74	1.60	11	3.80	2.04	4	4.9	0.97	3	4.6	3.4	7
H ₂	0.97	0.35	6	5	3.1	0.7	2.1	0.4	4	1.6	0.4	8	1.2	-	1	2.6	2.6-2.7	2
NO _x (as NO)	2.5	1.3	18	7	2.8	1.3	3.0	1.8	16	1.18	0.86	11	1.2	0.31-2.2	2	2.6	1.1	18
HONO	0.47	0.21	6	1	0.85	-	0.33	0.17	5	0.41	-	1	0.35	0.21-0.49	2	0.37	0.04	3
N ₂ O	0.18	0.09	11	0	0.20	-	0.25	0.12	3	0.24	0.06	5	-	-	0	0.09	0.04	5
NH ₃	0.90	0.49	16	4	1.34	0.78	0.98	0.69	22	2.5	1.75	4	4.2	3.2	3	0.93	0.62	13
HCN	0.44	0.26	16	5	0.64	0.21	0.64	0.39	12	0.53	0.30	11	4.4	1.2	3	0.43	0.19	6
Cyanogen, (CN) ₂	-	-	0	0	-	-	-	-	0	-	-	0	-	-	0	-	-	0
N ₂	2.6	-	0	0	2.6	-	2.6	-	0	2.6	-	0	-	-	0	2.6	-	0
SO ₂	0.47	0.44	12	0	0.77	0.37	0.70	0.48	5	0.75	0.14-0.31	2	4.3	-	1	0.80	0.71	10
Dimethyl sulfide (DMS)	0.008	0.011	5	1	0.022	-	0.014	0.015	3	0.023	-	1	0.045	0.003-0.088	2	0.07	-	1
COS	0.038	0.045	4	0	0.078	0.046	0.035	0.044	6	0.058	0.031	3	0.110	-	1	0.059	0.070	4
HCl	0.13	0.10	3	0	0.13	-	0.039	0.031	3	0.13	-	0	0.008	-	1	0.18	0.255	3
CH ₃ Cl	0.064	0.067	15	0	0.029	0.02-0.04	0.042	0.056	8	0.060	0.033	4	0.15	-	1	0.16	0.13	4
CH ₃ Br	0.0029	0.0052	13	0	0.0078	0.005-0.010	0.0015	0.010	3	0.0029	0.0011	4	0.010	-	1	0.0011	-	1
CH ₃ I	0.0007	0.0006	9	0	0.0068	-	0.0005	0.0004-0.001	2	0.0004	-	1	0.012	-	1	0.0002	-	1
Hg ⁰	4.8E-05	4.2E-05	4	1.0E-04	8.3	4.7E-5-1.7E-4	2.0E-04	1.8E-04	6	2.3E-04	3.0E-04	6	-	-	0	5.1E-05	5.0E-05	3
PM _{2.5}	6.7	3.3	20	9	18.1	3.3	14.5	14.5	28	18.7	15.9	5	17.3	-	1	8.2	4.4	18
TPM	8.7	3.1	11	11	10.9	5.3	18.4	8.3	11	15.3	12.3-18.3	2	26.2	-	0	11.6	8.1	5
TC	3.2	1.5	10	5	5.5	1.6	8.4	2.2	3	9.9	-	0	12.6	-	0	4.9	3.9	18
OC	2.8	1.3	13	4	4.4	1.9	9.4	5.6	12	7.5	-	1	12.4	-	1	4.5	3.6	16
BC	0.53	0.37	17	8	0.51	0.34	0.55	0.36	14	0.53	0.08	3	0.19	-	1	0.42	0.27	20
Levoglucosan	0.05	-	1	0	0.42	-	1.32	1.21	6	1.3	-	1	0.57	-	1	0.73	0.66	6
K	0.40	0.24	12	4	0.32	0.22	0.17	0.16	4	0.17	-	0	0.004	-	1	0.49	0.46	8
CN	2.7E+16	2.4E+16	4	3.9E+15	1.3E+15	-	9.9E+15	3.4E+15	0	4.2E+15	-	1	-	-	0	5.4E+15	2.2E+15	3
CCN (0.5% SS)	7.9E+14	-	1	1.7E+15	1.65E+15-1.68E+15	-	2.0E+15	3.4E+15	3	1.6E+15	-	0	-	-	0	1.0E+15	-	0
N(≅~0.12 μm diameter)	9.1E+14	6.1E+14	3	2.7E+15	-	-	1.0E+15	-	0	1.0E+15	-	0	-	-	0	1.0E+15	-	0



a) Emission factors are given in gram species per kilogram dry matter burned. See text for the conventions used for reporting uncertainties. Abbreviations are as follows: PM_{2.5}, particulate matter <2.5 mm diameter; TPM, total particulate matter; TC, total carbon; BC, black carbon; CN, condensation nuclei; CCN(0.5% SS), cloud condensation nuclei at 0.5% supersaturation; and N(*>*-0.12 mm diam), particles >-0.12 μm diameter. Values in italics represent estimates for emission factors that have not been measured directly.

b) Estimation method for emission factors for which no measurements are available. See text section 2.4 for details.



Table 1 (continued)

Species	Biofuels (without dung)		Dung		Charcoal making		Charcoal burning		Garbage burning		Lab studies	
	average	std.dev.	N	average	std.dev.	N	average	std.dev.	N	average	std.dev.	N
MCE	0.92	0.03	39	0.88	0.04	9	0.79	0.04	8	0.88	0.04	15
CO ₂	1550	170	36	1050	230	9	490	70	7	2500	350	14
CO	83	29	61	89	42	14	93	39	9	207	63	17
CH ₄	6.8	6.0	28	8.9	4.9	8	19.0	19.9	8	6.0	2.6	9
Total NMHC	7.8	5.0	23	14.4	10.0-18.8	2	26.4	18.1	4	6.6	4.9	6
C ₂ H ₂	0.68	0.37	14	0.68	0.41	3	0.28	0.24	3	0.27	0.18	4
C ₂ H ₄	1.33	0.90	15	2.25	1.36	4	1.51	0.34	6	0.51	0.34	6
C ₂ H ₆	0.63	0.61	13	1.28	0.70	3	2.4	1.3-3.4	2	0.76	0.34	5
C ₃ H ₄	0.13	0.14	3	0.11	0.06	3	0.09	-	0	0.21	-	0
C ₃ H ₆	0.40	0.29	13	1.45	0.46	4	1.03	0.32	4	0.53	0.19	3
C ₃ H ₈	0.24	0.25	7	0.50	0.31	3	0.53	-	1	0.17	0.12	3
1-Butene	0.23	0.24	9	0.31	0.131	3	-	0	0	0.12	0.040-0.20	2
i-Butene	0.26	0.33	6	0.26	0.11	3	-	0	0	0.091	0.026-0.16	2
trans-2-Butene	0.05	0.03	3	0.12	0.06	3	-	0	0	0.040	0.016-0.063	2
cis-2-Butene	0.04	0.02	3	0.081	0.041	3	-	0	0	0.025	0.016-0.034	2
Butadiene	0.15	0.10	9	0.30	0.10	3	-	0	0	0.11	0.09	3
n-Butane	0.19	0.18	7	0.18	0.12	3	-	0	0	0.074	0.053-0.095	2
i-Butane	0.15	0.22	3	0.10	0.10	3	-	0	0	0.012	0.010-0.013	2
1-Pentene	0.03	0.03	6	0.11	0.06	3	-	0	0	0.028	-	1
2-Pentenes	0.02	0.02-0.02	2	0.090	0.071	3	-	0	0	0.057	-	0
n-Pentane	0.018	0.021	8	0.093	0.088	3	-	0	0	0.096	-	1
2-Methyl-butenes	0.014	0.012	3	0.036	0.021	3	-	0	0	0.015	-	1
2-Methyl-butane	0.045	0.043	4	0.34	0.41	3	-	0	0	0.071	-	1
n-Pentadienes	0.017	0.015	4	0.039	0.02-0.06	2	-	0	0	0.083	-	0
Isoprene	0.06	0.05	10	0.20	0.12	3	-	0	0	0.12	0.017-0.22	2
n-Hexane	0.008	-	1	0.018	-	0	-	0	0	0.035	-	1
Cyclopentadiene	0.061	0.047	4	0.80	-	0	-	0	0	0.070	-	0
4-Methyl-1-pentene	0.015	-	1	0.032	-	0	-	0	0	0.074	-	0
2-Methyl-1-pentene	0.029	-	0	0.032	-	0	-	0	0	0.074	-	0
1-Hexene	0.018	0.007	5	0.11	0.06-0.17	2	-	0	0	0.11	-	0
Hexadienes	0.006	-	0	0.006	-	0	-	0	0	0.01	-	0
n-Hexane	0.009	0.006	6	0.12	0.15	3	-	0	0	0.185	0.063-0.31	2
Isobutanes	0.065	0.084	3	0.18	0.28	3	-	0	0	0.10	-	0
Heptanes	0.005	0.003	6	0.11	-	1	-	0	0	0.047	-	0
Octenes	0.007	0.014	4	0.016	-	0	-	0	0	0.036	-	0
Terpenes	0.10	0.14	7	0.12	0.199	3	-	0	0	0.092	-	0
Benzene	0.95	0.89	17	1.25	0.63	3	-	0	0	1.23	0.72-1.7	2
Toluene	0.45	0.51	14	0.87	0.39	3	-	0	0	0.41	0.20-0.62	2
Xylenes	0.13	0.15	10	0.32	0.282	3	-	0	0	0.16	0.099-0.23	2
Ethylbenzene	0.10	0.10	7	0.17	0.18	3	-	0	0	0.053	0.033-0.074	2
Styrene	0.18	0.19	8	0.13	0.11	3	-	0	0	0.14	0.066-0.22	2
PAHs	0.09	0.10	13	0.023	-	1	-	0	0	0.53	0.41-0.66	2
Methanol	2.0	1.1	9	3.2	1.1	4	13.0	6.1	3	1.0	0.72-1.24	2
Ethanol	0.075	0.02-0.13	2	0.23	0.29	3	0.060	-	0	0.13	-	0
1-Propanol	0.030	-	0	0.032	-	0	-	0	0	0.07	-	0
2-Propanol	0.10	-	0	0.10	-	0	-	0	0	0.24	-	0
Butanols	0.051	0.01-0.10	2	0.053	-	0	-	0	0	0.12	-	0
Cyclopentanol	0.028	-	0	0.030	-	0	-	0	0	0.07	-	0
Phenol	0.72	1.15	7	1.58	1.0-2.2	2	4.7	2.8-6.6	2	2.0	-	1
Formaldehyde	0.87	1.00	13	2.42	-	1	1.1	-	1	0.51	0.19	3
Acetaldehyde	0.41	0.32	13	1.46	0.58	3	-	0	0	0.13	0.62-2.3	2
Hydroxyacetalddehyde (glycolaldehyd.)	0.45	0.21	3	0.50	-	1	-	0	0	0.8	-	0
Glyoxal	0.38	-	1	0.57	-	0	-	0	0	7.2	-	0
Methylglyoxal	0.39	0.18-0.60	2	0.45	-	0	-	0	0	1.0	-	0
Acrolein (Propenal)	0.085	0.093	11	0.24	0.19-0.30	2	-	0	0	1.0	-	0
Propanal	0.072	0.069	8	0.12	-	0	-	0	0	0.27	-	0
Butanals	0.027	0.019	11	0.07	0.035	3	-	0	0	0.27	-	0
Methacrolein	0.028	0.025-0.031	2	0.14	-	0	-	0	0	0.32	-	0
Crotonaldehyde	0.22	-	1	0.31	-	0	-	0	0	0.73	-	0



Hexanals	0.006	0.003	0	0.028	-	0	0.07	-	0	0.021	-	0	0.006	0.003-0.008	2
Heptanals	0.003	-	0	0.004	-	0	0.009	-	0	0.003	-	0	0.007	0.004-0.011	2
Acetone	0.35	0.23	11	1.5	0.7	3	1.5	0.26	1	2.3	-	1	0.73	0.39	14
2-Butanone	0.095	0.064	12	0.31	0.17	3	0.66	0.30	1	0.21	-	1	0.27	0.23	11
2,3-Butanedione	0.21	0.01-0.41	2	0.62	-	0	1.4	0.65	0	0.45	-	0	0.63	0.44	9
1-Butene-3-one (Methylvinyl ketone)	0.058	0.05-0.07	2	0.20	0.13-0.28	2	0.57	0.255	0	0.18	-	0	0.29	0.13-0.46	2
Pentanones	0.029	-	1	0.055	-	0	0.13	-	0	0.040	-	0	0.086	0.079	4
Hexanones	0.045	-	0	0.048	-	0	0.11	-	0	0.035	-	0	0.017	0.007-0.027	2
Heptanones	0.004	-	0	0.004	-	0	0.009	-	0	0.003	-	0	0.063	0.009-0.12	2
Octanones	0.017	-	0	0.018	-	0	0.042	-	0	0.013	-	0	0.005	-	1
Benzaldehyde	0.044	0.048	8	0.070	-	0	0.16	-	0	0.051	-	0	0.071	0.030	10
Acetol (hydroxyacetone)	0.87	0.48-1.26	2	6.40	3.2-9.6	4	2.7	9.4	1	1.7	-	1	1.7	2.7	10
Furan	0.20	0.10	8	0.49	0.35	2	0.39	0.80	1	0.21	-	1	0.63	0.65	18
2-Methyl-furan	0.16	0.08	6	0.30	0.12-0.49	2	0.73	-	0	0.23	-	0	0.35	0.30	10
3-Methyl-furan	0.013	-	1	0.038	-	0	0.09	-	0	0.028	-	0	0.23	0.37	4
2-Ethyl-furan	0.005	-	0	0.006	-	0	0.013	-	0	0.004	-	0	0.007	-	1
2,4-Dimethyl-furan	0.003	0.001	3	0.009	-	0	0.021	-	0	0.007	-	0	0.010	-	1
2,5-Dimethyl-furan	0.035	0.009	3	0.073	-	0	0.17	-	0	0.053	-	0	0.15	0.18	8
Tetrahydrofuran	0.008	-	0	0.008	-	0	0.019	-	0	0.006	-	0	0.002	0.002-0.002	2
2,3-Dihydrofuran	0.009	-	0	0.009	-	0	0.022	-	0	0.007	-	0	0.034	0.10	9
Benzofuran	0.046	-	1	0.045	-	0	0.10	-	0	0.033	-	0	0.108	0.68	9
Furfural (2-Furaldehyde)	0.28	0.37	5	0.20	0.09-0.32	2	1.6	-	0	0.49	-	0	0.043	-	1
Methyl formate	0.040	-	0	0.043	-	0	0.10	-	0	0.03	-	0	0.043	-	1
Methyl acetate	0.105	0.05-0.17	2	0.11	-	0	0.27	-	0	0.08	-	0	0.087	0.101	3
Acetonitrile	0.10	0.02-0.18	2	-	-	0	-	-	0	-	-	0	0.16	0.16	15
Acrylonitrile	0.030	-	1	-	-	0	-	-	0	-	-	0	0.082	0.12	5
Propionitrile	-	-	0	-	-	0	-	-	0	-	-	0	0.14	0.27	5
Pyrrrole	-	-	0	-	-	0	-	-	0	-	-	0	0.16	0.22	3
Trimethylpyrazole	-	-	0	-	-	0	-	-	0	-	-	0	0.124	-	1
Methylamine	-	-	0	-	-	0	-	-	0	-	-	0	0.057	-	1
Dimethylamine	-	-	0	-	-	0	-	-	0	-	-	0	0.062	-	1
Ethylamine	-	-	0	-	-	0	-	-	0	-	-	0	0.005	0.0004-0.010	2
Trimethylamine	-	-	0	-	-	0	-	-	0	-	-	0	0.041	-	1
n-Pentylamine	-	-	0	-	-	0	-	-	0	-	-	0	0.44	-	1
2-Methyl-1-butylamine	-	-	0	-	-	0	-	-	0	-	-	0	0.14	-	1
Formic acid	0.31	0.27	6	0.63	0.34-0.91	2	0.39	0.33-0.45	2	0.12	0.04	3	0.42	0.38-0.45	26
Acetic acid	3.9	3.7	6	10.8	7.3-14.3	2	47	47	3	1.85	0.49-3.2	2	1.6	0.87-2.4	30
H ₂	1.8	-	0	2.0	-	0	-	-	0	4.6	-	0	1.4	-	0
NO _x (as NO)	1.3	0.7	18	2.7	3.9	5	0.24	0.43	5	2.3	1.8	7	2.2	-	32
HONO	0.37	0.29-0.45	2	0.26	0.24-0.28	2	0	0	0	0.30	0.17-0.42	2	0.49	-	17
N ₂ O	0.07	0.02	4	0.31	-	1	0.025	0.014	4	0.34	0.37	3	-	0.071	4
NH ₃	0.42	0.51	5	3.1	2.2	4	3.8	7.2	4	0.72	0.49	4	0.90	0.67-1.12	27
HCN	0.39	0.22-0.56	2	1.27	0.53-2.0	2	0.09	-	1	-	-	0	0.43	1.00	23
Cyanogen, (CN) ₂	-	-	0	-	-	0	-	-	0	-	-	0	0.007	-	1
N ₂	2.6	-	0	-	-	0	-	-	0	-	-	0	4.1	-	1
SO ₂	0.56	0.70	14	0.66	0.60	4	0.20	-	1	0.57	0.55	3	-	0.92	23
Dimethyl sulfide (DMS)	0.12	0.13	3	0.025	0.017	3	-	-	0	-	-	0	0.007	0.19	8
COS	0.017	0.01-0.02	2	0.21	0.13	3	-	-	0	-	-	0	0.074	0.040	3
HCl	0.075	-	1	0.038	-	1	-	-	0	0.11	-	1	2.3	0.25	7
CH ₃ Cl	0.184	0.278	6	2.2	2.2	3	-	-	0	0.011	-	1	0.70	0.15	8
CH ₃ Br	0.0007	0.0006-0.0008	2	0.0087	0.0049	3	-	-	0	-	-	0	0.002	0.0005-0.001	2
CH ₃ I	0.0001	0.0001-0.0001	2	0.0006	0.0002	3	-	-	0	-	-	0	0.0003	-	0
Hg ⁰	4.7E-05	6.8E-6-8.8E-5	2	-	-	0	-	-	0	-	-	0	-	-	1
PM _{2.5}	6.9	4.4	57	16.5	13.0	8	20.1	2.1-38.2	2	3.0	2.5	7	7.4	11.3	22
TPM	7.0	5.8	27	6.1	6.0	5	13.8	19.3	4	2.1	1.7-2.4	2	-	8.1	12
TC	3.4	1.4	28	8.1	9.9	4	-	-	0	2.0	2.0	5	6.9	9.1	7
OC	3.1	2.0	65	10.2	9.4	6	0.8	-	1	2.2	2.0	4	5.5	5.3-5.7	22
BC	0.81	1.20	65	0.31	0.26	7	0.02	-	1	0.27	0.15	3	1.4	4.5	25
Levoglucosan	0.50	0.42	13	0.45	0.16-0.74	2	0.06	-	1	0.79	-	1	0.40	0.25-0.56	12
K	0.13	0.24	22	0.09	0.10	4	0.004	-	1	0.75	0.79	3	0.02	0.01-0.02	20
CN	2.9E+15	3.0E+15	4	-	-	0	-	-	0	4.9E+15	2.5E+15-7.2E+15	2	5.7E+15	0.36	3
CCN (0.5% SS)	1.1E+15	-	0	-	-	0	-	-	0	-	-	0	-	1.1E+15	1
N(≈0.12 μm diameter)	1.0E+15	-	0	-	-	0	-	-	0	-	-	0	-	8.0E+14	0



Table 2: Estimates of biomass burned (Tg dry matter) annually in the various fire categories

Source	Savanna/ grassland	Tropical forest	Temperate forest	Boreal forest	Peat	Agricultural residues	Total open fires	Years
FINN ^a	1920	3200	260	137	---	210	5730	2005-2010
GFED4.1s ^b	2980	690	100	330	161	290	4550	2005-2015
GFAS1.2 ^c	2540	910	110	460	183	63	4260	2003-2018
QFED ^d	3690	850	280	200	---	---	5560	2003-2012
FEER ^e	---	---	---	---	---	---	9330	2000-2012
FLAMBE ^f	870	8750	750	1120	---	99	11580	2005-2015
ECLIPSE V6a ^g	---	---	---	---	---	530	---	2005-2010
Average	2400	2880	300	450	172	240	6440	
	Wood etc.	Charcoal making	Charcoal burning	Agricultural waste	Dung		Total biofuel	
Fernandes ^h	1350	156	39	500	75		2120	2000
FAO ⁱ	---	---	53	---	---		---	2014
ECLIPSE V6a ^g	1780	---	44	350	89		2270	2005-2010
CEDS ^j	1590	---	46	580	88		2490	2010
Average	1570	180	45	480	84		2360	
Grand total from all biomass burning							8800	

^a)Wiedinmyer et al. (2011)

^b)from http://www.geo.vu.nl/~gwerf/GFED/GFED4/tables/GFED4.1s_C.txt assuming 45% C in biofuel

^c)I. Hüser, personal communication 2019, based on methodology in Kaiser et al. (2012)

^d)A. Darmenov, personal communication 2019, based on methodology in Darmenov and da Silva (2015). Emissions from boreal fires were calculated from extratropical fires north of 50 °N, and temperate emissions were calculated by subtracting boreal from extratropical emissions; emissions from crop residue burning fires are included in the grassland fire category.

^e)Ichoku and Ellison (2014), not included in category averages because breakdown not available

^f)E. Hyer, personal communication 2019, based on methodology in Reid et al. (2009). Temperate and boreal emissions were calculated by splitting extratropical burning 40%/60%.

^g)Z. Klimont, personal communication 2019, based on methodology in Klimont et al. (2017)

^h)Fernandes et al. (2007)

ⁱ)FAO (2015)

^j)S. Smith, personal communication 2019, based on methodology in Hoesly et al. (2019)

Table 3: Global emission of selected species based on the emission factors in Table 1 and the biomass burning estimates in Table 2 (Tg a^{-1}).

Tg dm burned	Savanna and grassland	Tropical forest	Temperate forest	Boreal forest	Peat fires	Agricultural residues	Biofuel burning	Charcoal making	Charcoal burning	Total	A&M2001
	2400	2880	300	450	172	240	2134	180	45	8800	8600
CO ₂	3980	4670	470	690	270	340	3310	90	110	13900	13400
CO	170	300	34	55	43	18	180	17	9.4	820	690
CH ₄	5.9	18	1.6	2.5	1.6	1.3	15	3.4	0.27	49	39
Total NMHC	8.5	16	4.0	2.7	3.2	1.4	17	4.8	0.30	58	49
C ₂ H ₂	0.77	1.0	0.09	0.13	0.02	0.07	1.4	0.05	0.012	3.6	3.7
Methanol	3.2	8.1	0.6	1.0	0.4	0.6	4.3	2.3	0.04	21	12.7
Formaldehyde	2.9	6.9	0.6	0.8	0.2	0.4	1.9	---	0.02	14	5.5
Acetaldehyde	2.0	6.5	0.32	0.37	0.20	0.41	0.87	---	0.01	10.7	3.5
Acetone	1.1	1.81	0.17	0.72	0.16	0.15	0.74	0.05	0.07	5.0	3.0
Acetonitrile	0.40	1.43	0.07	0.14	0.10	0.06	0.21	---	---	2.4	1.3
Formic acid	0.7	2.5	0.3	0.9	0.1	0.2	0.67	0.07	0.01	5.5	5.9
Acetic acid	5.6	9.5	0.8	1.7	0.8	1.1	8.4	8.4	0.08	36	12.6
H ₂	2.3	8.9	0.6	0.7	0.2	0.6	3.9	---	0.21	18	15.3
NO _x	6.0	8.1	0.9	0.5	0.2	0.6	2.7	0.04	0.11	19	21
N ₂ O	0.43	0.58	0.08	0.11	---	0.02	0.15	0.00	0.016	1.38	1.31
NH ₃	2.1	3.8	0.29	1.11	0.71	0.2	0.9	0.68	0.03	9.9	10.3
HCN	1.06	1.26	0.19	0.24	0.76	0.10	0.83	0.02	---	4.5	0.9
N ₂	6.3	7.6	0.8	1.2	---	0.6	5.6	---	---	22	26
SO ₂	1.1	2.22	0.21	0.34	0.73	0.19	1.20	---	0.026	6.0	3.5
COS	0.09	0.22	0.01	0.03	0.02	0.01	0.04	---	---	0.42	0.27
CH ₃ Cl	0.15	0.08	0.01	0.03	0.03	0.04	0.39	---	0.0005	0.73	0.65
CH ₃ Br	0.007	0.022	0.000	0.001	0.002	0.000	0.001	---	---	0.035	0.029
CH ₃ I	0.0016	0.0196	0.0001	0.0002	0.0021	0.0000	0.0002	---	---	0.024	0.014
Hg	0.0001	0.0003	0.00006	0.00010	---	0.00001	0.0001	---	---	0.0007	0.0008
PM _{2.5}	16	24	5.4	8.4	3.0	2.0	14.7	3.6	0.14	77	58
TPM	21	31	5.5	6.9	0.0	2.8	14.9	2.5	0.09	85	82
TC	7.6	16	2.5	4.5	2.2	1.2	7.3	---	0.09	41	42
OC	6.7	12.8	2.8	3.4	2.1	1.1	6.7	---	0.10	36	36
BC	1.3	1.46	0.17	0.24	0.03	0.10	1.7	---	0.01	5.0	4.8
K	0.95	0.93	0.05	0.08	0.001	0.12	0.28	---	0.03	2.4	1.9
CN	6.6E+28	1.1E+28	3.0E+27	1.9E+27	---	1.3E+27	6.3E+27	---	2.2E+26	9.0E+28	2.9E+28
CCN (1% SS)	1.9E+27	4.8E+27	6.0E+26	7.4E+26	---	2.4E+26	2.4E+27	---	---	1.1E+28	1.7E+28
N(acc)	2.2E+27	7.9E+27	3.0E+26	4.5E+26	---	2.4E+26	2.1E+27	---	---	1.3E+28	9.0E+27

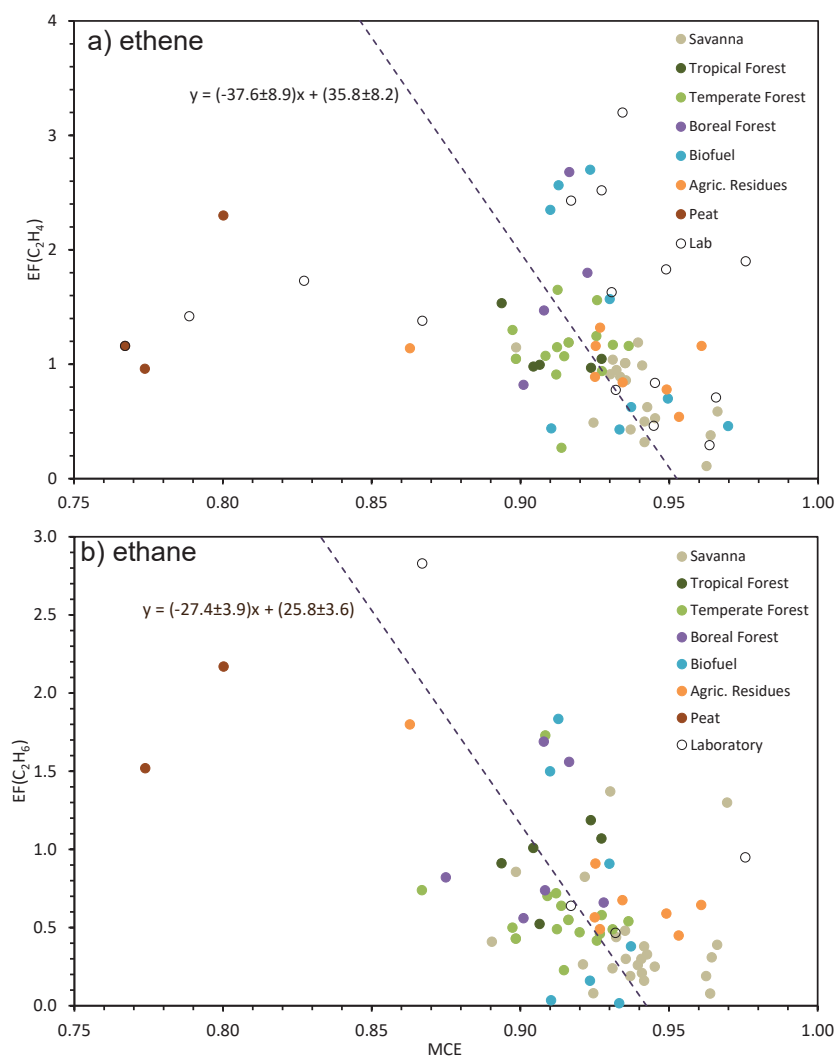


Figure 1: Scatter plots of the emission factors of ethene (a) and ethane (b) against MCE, based on studies in the different combustion categories.